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Original Research Paper

Mechanical performance of cold mix asphalt containing cup lump rubber as a sustainable bio-modifier

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HIGHLIGHTS

- The effect of cup lump rubber on mechanical performance of CMA mixture is studied.
- The polymeric potential of cup lump rubber enhances the cracking resistance of cold mix asphalt.
- Cup lump rubber prevents rutting and improves resistance to moisture damage of CMA.
- Cup lump rubber enhances bonding strength and interlocking structure of CMA.
- The durability and stripping resistance was enhanced by the addition of cup lump rubber.

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ABSTRACT

The road construction industry aims to contribute to the protection of already compromised environment. Cold mix asphalt (CMA) is a measure initiated by the road industry to protect the environment and preserve energy. Despite having additional benefits, CMA has attracted little attention due to its inferior performance. CMA's performance is enhanced using a sustainable binder bio-modifier, natural cup lump rubber (CLR) is one of them. This study evaluated the tensile properties, rutting, moisture susceptibility, and adhesion properties of CLR-modified CMA (CMA-CR). The tensile property was enhanced by 26% due to CLR modification. CMA-CR had excellent rutting resistance of less than 2 mm rut depth at 10,000 load cycles, showing 70% improvement compared with conventional CMA. Moisture susceptibility evaluation indicated that CMA-CR had tensile strength ratio (TSR) value of 104%, satisfying the minimum 80% requirement of AASHTO T283. It also retained more than 96% bitumen coating. The moisture damage resistance was improved by 12% and 10% in terms of TSR and stripping, respectively. The durability results revealed that the CMA-CR mixture prevented higher mass loss, representing 14% improvement compared with conventional CMA.

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Abbreviations

AI-MS	Asphalt institute manual
BB-8	Bitumen of 80/100 PEN grade
BB-6	Bitumen of 60/70 PEN grade
BE-CR	Cup lump-modified bitumen emulsion
BE-8	Bitumen emulsion prepared from BB-8
BE-6	Bitumen emulsion prepared from BB-6
C	Carbon
CR	Chloroprene rubber
CLR	Cup lump rubber
CMB	Cup lump-modified bitumen
CMA	Cold mix asphalt
CMA-CR	Cup lump modified cold mix asphalt
CMA-8	Cold mix asphalt using BE-8
CMA-6	Cold mix asphalt using BE-6
CSM	Creep stiffness modulus
CSS	Creep strain slop
DWT	Double-wheel tracking
EDX	Energy-dispersive X-ray
EVA	Ethylene vinyl acetate
G_{mb}	Bulk specific gravity
G_{mm}	Theoretical maximum specific gravity
HMA	Hot mix asphalt
HWMA	Half-warm mixture
IEC	Initial emulsion content
IDT	Indirect tensile strength
IRBC	Initial residual bitumen content
JKR	Jabatan Kerja Raya
MS	Medium setting
Mg	Magnesium
M_R	Resilient modulus
NR	Natural rubber
Na	Sodium
O	Oxygen
OTLC	Optimum total liquid content at compaction
OPC	Ordinary Portland cement
OEC	Optimum emulsion content
ORBC	Optimum residual bitumen content
P	Phosphorus
PU	Polyurethane
PWD	Malaysian public works department
RPM	Revolution per minute
RBC	Residual bitumen content
S	Sulfur
SS	Slow setting
Si	Silicon
SEBS	Styrene-ethylene-butylene-styrene
SBR	Styrene butadiene rubber
SBS	Styrene butadiene styrene
TSR	Tensile strength ratio
TMD	Theoretical maximum density
VTM	Voids in total mixture
VMA	Voids in mineral aggregate
VFB	Voids filled with bitumen
WMA	Warm mix asphalt

1. Introduction

Environment-friendly and cost-efficient methods have become the main priority for the road construction industry (Ansari et al., 2021; Jain and Singh, 2021). A major portion of energy is consumed by conventional road construction within transport industry, resulting in 72% of the total hazardous gases emitted in the environment (Abdulrahman et al., 2021). Hence, researchers are concerned to protect the environment and preserve energy (Alam et al., 2020; Al-Sabaeei et al., 2020). Hot mix asphalt (HMA) pavement is dealt at an elevated temperature up to 180 °C. Warm mix asphalt (WMA) and half-warm mixture (HWMA) are produced at 110 °C–140 °C and below 100 °C, respectively, which are still considered elevated temperatures (Bhanuprasad et al., 2014). Relevant studies on the impact of road construction on the environment are discussed briefly (Airey, 2004; Capitão et al., 2012; Navarro et al., 2009; Sheng et al., 2018).

The road industry currently focuses on protecting the environment and saving energy by using cold mix technology, which can be used to construct sustainable road infrastructures. In addition, CMA can be fabricated at ambient temperature by using emulsified bitumen as a binder in the mixture (Nassar et al., 2018; Yaro et al., 2022). This emulsified binder used in CMA can reduce the binder viscosity at ambient temperature, resulting in six time less energy consumption as required by HMA production (Yuliestyan et al., 2016). Thus, CMA using emulsified bitumen as a binder is better than the production of HMA and WMA in the perspective of energy consumption, cost efficiency, and environment friendliness (Jain and Singh, 2021; Lu et al., 2013).

Despite its several benefits, CMA faces some major concerns in terms of mechanical performance, such as high porosity, low early strength, and extra curing time required (Deb and Lakshman Singh, 2022). These problems are well supported by the lower adhesion potential of CMA and high sensitivity to moisture. Therefore, it cannot meet the traffic and environmental conditions required for pavement structural layers (Shanbara et al., 2017; Thanaya, 2007; Thanaya et al., 2009). Hence, the application of CMA is limited in the maintenance work of road pavements, including patching, potholes (Boateng et al., 2022).

The physical properties of the emulsified binder of CMA need to be modified by adding polymers for its continuous application in road construction (Yao et al., 2022). Commonly used modifiers in CMA binder modification include styrene butadiene styrene (SBS), styrene butadiene rubber (SBR), crumb rubber, ethylene vinyl acetate (EVA), natural rubber (NR) latexes, and water-based epoxy resins (Jiang et al., 2018; Khadivar and Kavussi, 2013; McNally, 2011). These polymers are employed to modify bitumen emulsions based on their physical, chemical, and reactive group properties (Ma et al., 2017). Moreover, the elastomeric and thermoplastic properties of these modifiers confer better performance than pure binder (Dalhat and Al-Adham, 2023; Li et al., 2022; Masson et al., 2001). These polymers can support the enhancement of the physical properties of the end residues of bitumen emulsions, leading to greater mechanical performance of the CMA mixture. The physical properties of modified bitumen emulsion residues include penetration, softening point, viscosity, and elasticity (King and Johnston, 2012; Pan et al., 2019).

An extensive literature exists on the performance enhancement of CMA mixed with different types of polymers. Bitumen emulsions modified with SBS and EVA were used to prepare CMA mixtures to prevent permanent deformation and improve stiffness (Deb and Lakshman Singh, 2022; Shanbara et al., 2021). In another study (Jiang et al., 2018), modified bitumen emulsions were prepared with three different types of polymers, such as SBR latex, styrene-ethylene-butylene-styrene (SEBS) copolymer, and chloroprene rubber (CHR) latex; the CMA mixtures of modified bitumen emulsions performed better in terms of rutting resistance. Xu et al. (2014) studied the effect of a potential modifier on the resistance of cracking and moisture damage of a CMA. The application of epoxy resin and SBR latex in CMA resulted in enhanced mechanical and adhesion strength (Li et al., 2019; Xu et al., 2022; Zamanian et al., 2013). Recently, 15%–30% epoxy resin was employed to produce modified bitumen emulsion, leading to enhanced flexural tensile strength and adhesive performance of the CMA (Cai et al., 2020). Furthermore, the moisture resistance of the CMA was enhanced using polyurethane (PU)-modified cold binder (Min et al., 2019). Rubberized and waste-employed cold binders are also widely applied in CMA to improve their mechanical performance (Makoundou and Sangiorgi, 2022; Rahman et al., 2020; Razali et al., 2020).

Natural rubber, which is a locally produced bio-polymer by collecting from bark of rubber trees in the form of runny milky liquid into the cups by tapping known as cup lump rubber (CLR). CLR sustains high fatigue resistance, stretch ratio and water resistance (Ikeda et al., 2018). Therefore, it has been applied to road pavements for decades due to its cost-effectiveness and sustainability toward green environment (Al-Sabaeei et al., 2019; Ansari et al., 2022). Due to CLR's potential at high temperature, it enhances shear resistance by membrane effect (Abdulrahman et al., 2023). Thus, it is applied to road pavements by Malaysian Public Works Department (PWD). Cup lump modified asphalt has similar potential to HMA in terms of mechanical strength (Othman et al., 2018). The potential elastic properties of CLR can mitigate rutting in HMA (Shaffie et al., 2017). Recently, CLR has been used in WMA to improve its physical and mechanical properties (Abdulrahman et al., 2019). The use of 5% CLR in HMA and WMA significantly enhanced its mechanical and rheological properties. Moreover, CLR has environmental benefits in terms of low carbon emission (Abdulrahman et al., 2019; Azahar et al., 2019, 2021; Shaffie et al., 2017). However, the compatibility issues of polymer with bitumen persist and high shear mixing is required for some polymers. Emulsification becomes difficult with a high concentration of polymers because it is limited to 3%; beyond this value, the emulsified bitumen cannot meet the stability specifications (Cai et al., 2010). According to a recent study by Ghafar et al. (2022a), the modification of bitumen emulsion with 3% CLR enhanced the physical properties and resulted in satisfactory compatibility with bitumen. However, research on CLR rubber in CMA mixtures has not been conducted yet, highlighting the importance of evaluating the effect of CLR rubber on the mechanical performance of CMA mixtures. In addition, the potential characteristics of CLR could be utilized to develop a sustainable polymer-modified CMA mixture to promote environmental sustainability and cost efficiency in road construction and CLR production.

2. Materials and research methods

This section elaborates the research framework, including the materials, experimental methods, specifications, and laboratory equipment used for the study. Fig. 1 presents the research flowchart.

2.1. *Materials*

The base bitumen of 80/100 PEN grade (BB-8) and 60/70 PEN grade (BB-6) were obtained from Asphalt Technology Selangor, Malaysia. The physical properties of bitumen are given in Table 1. CLR rubber was supplied by Chip Hong Rubber Factory for bitumen modification. The elemental composition of CLR was obtained through energy-dispersive X-ray (EDX) test as depicted in Fig. 2. Carbon (C) was the dominant element in CLR, followed by oxygen (O) at 12% and other elements such as silicon (Si), sulfur (S), sodium (Na), magnesium (Mg), and phosphorus (P). Cationic-type emulsifier (Redicote EM44) was obtained from Nouryan for emulsification of the modified bitumen. The physical properties of the emulsifier are presented in Table 2. Crushed granite aggregates were supplied by Hanson Heidelberg Cement Group, Kulai, Johor Bahru. The basic characteristics of crushed granite are given in Table 3.

2.2. *Modified bitumen preparation*

The production of cup lump-modified bitumen (CMB) was purely based according to the method developed by Ghafar et al. (2022a). The CLR was cut into pieces of 10 mm size and soaked into softener (toluene) for 24 h. The CLR toluene ratio was limited to 1:2. This pre-treatment converted CLR into a

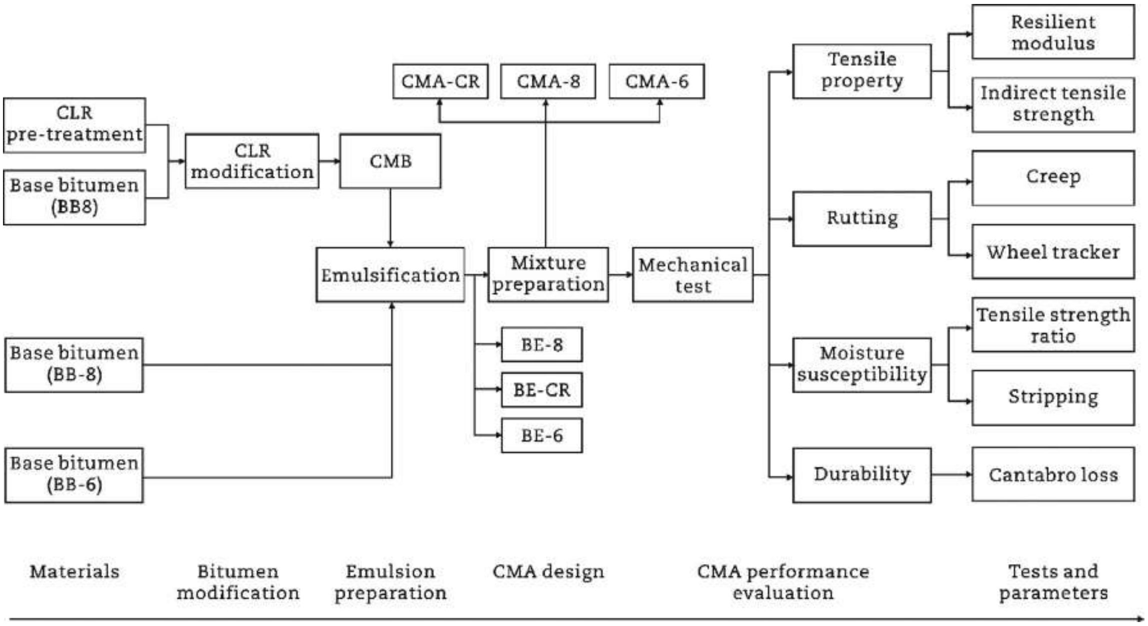

Fig. 1 – Research flow chart.

gel structure. Base bitumen BB-8 was selected for modification with CLR. Softer grades are recommended for emulsification, and polymer modification causes bitumen to enhance the PEN grade. Hence, hard-grade bitumen is difficult to emulsify. As such, the effective percentage of 3% CLR was selected for modification with bitumen given that bitumen modified with higher than 3% exhibited clogging and inability to emulsify. Previous studies recommend adding polymers by up to 3% only (Becker et al., 2001; King and Johnston, 2012). CMB was prepared by adding 3% CLR and blended with a high shear mixer at 4000 rpm and (160 ± 10) °C for 2 h. An extensive research is available on the pre-treatment of CLR rubber and mixing parameters (Abdulrahman et al., 2021; Azahar et al., 2021; Ghafar et al., 2022a, 2022b). The physical properties of prepared CMB are given in Table 4.

2.3. *Modified bitumen emulsion preparation*

Emulsification was performed through colloid milling by pouring soap solution followed by heated CMB. The bitumen to water ratio was set to 60:40. The solution was prepared by dissolving 5% emulsifier in heated water at constant pH value of 2–3. The heated bitumen was poured into the colloid mill and mixed with the solution for 9 min at a shearing speed of 2840 rpm. The soup solution and CMB were heated up to 50 °C and 160 °C prior to mixing. In addition, two types of bitumen emulsions without CLR modification were prepared using BB-8 and BB-6 as control samples. The emulsifier dosages for BB-8 and BB-6 were 0.5% and 1.0%, respectively. Formulation parameters, such as emulsifier content, temperature, and mixing time, were optimized before emulsification. Finally, bitumen emulsions, namely, cup lump-modified bitumen emulsion (BE-CR), bitumen emulsion prepared from BB-8 (BE-8), and bitumen emulsion prepared from BB-6 (BE-6), were used to prepare CMA mixtures. The physical properties of prepared bitumen emulsions are presented in Table 5.

Table 1 – Physical properties of bitumen.

Property	BB-8	BB-6
Penetration (25 °C, 0.1 mm)	97	68
Softening point (°C)	43	47
Viscosity at 135 °C (Pa·s)	0.27	0.65
Penetration index	−1.55	−1.27

2.4. *Mixture design*

The procedure recommended by Asphalt Institute Manual (AI-MS-14) was used to design CMA mixture due to its simplification and availability of test equipment (Asphalt Institute, 1989). Three types of CMA mixtures were designed, namely, CMA-CR, CMA-8, and CMA-6, by using BE-CR, BE-8, and BE-6 bitumen emulsions, respectively. The procedural steps followed in the mixture design were based on a previous study by Thanaya (2007). Moreover, the ordinary Portland cement (OPC) in CMA mixture is recommended for its early mechanical strength (Dash et al., 2022; Jain and Singh, 2021). This study limited to use 2% OPC with replacement of mineral filler.

Moreover, the selection of an appropriate aggregate gradation is mandatory in CMA mixture design because it affects the mechanical performance of the mixture (Brown and Needham, 2000). A uniform dense gradation was adopted to design CMA for all types of bitumen emulsion (Fig. 3). The selection of gradation was based up on empirical formula for initial residual bitumen content (IRBC) determination as recommended by AI. The selected gradation also meets the Jabatan Kerja Raya (JKR)

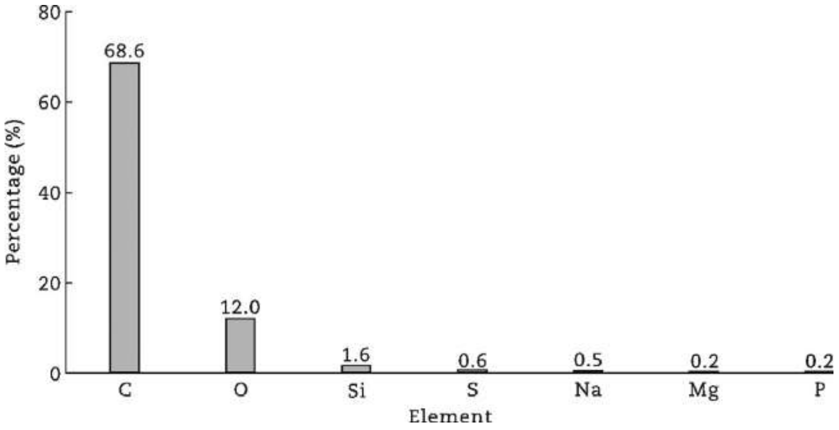

Fig. 2 – Elemental composition of CLR rubber.

specifications of dense graded mixes for surface bituminous courses used in Malaysia (JKR, 2008). Similarly, IRBC is the percent of residual bitumen of the total mixture required for its initial stability requirement and it was found to be 6.5% for all three types of mixtures.

Furthermore, the initial emulsion content (IEC) values were calculated to be 10.5%, 9.8%, and 10.2% for CMA-8, CMA-CR, and CMA-6, respectively. The IEC value depends on the passing or retained percentages on sieves 2.36 and 0.075 mm and residual bitumen content (RBC) also influences the IEC value (Ling and Bahia, 2018; Rezaei et al., 2017). Subsequently, initial compatibility assessment between bitumen emulsion and aggregates was conducted through coating test (Shanbara et al., 2021). An additional amount of water is required to ensure sufficient coating, workability, and aggregate lubrication of the CMA mixture (Sarella et al., 2022). The satisfactory aggregate coating criteria is set to 50% and 75% for base and wearing course by AI, respectively (Ling and Bahia, 2018). In the present study, a coating test was conducted with increasing moisture of 1% and it prevented aggregate coating; the impact increased with increasing amount of water. Therefore, the addition of pre water was avoided in this CMA mixture design. A previous work (Usman et al., 2021) also reported that the added pre water discouraged the aggregate coating and resulted in stripping.

2.5. *Mixture preparation*

This study adopted the modified Marshall method (ASTM, 2020c; Asphalt Institute, 1989) for the preparation of CMA samples with some minor modifications. Manual mixing by hand with a large spoon was conducted, limiting the mixing time to a maximum of 3 min. The homogenous mixtures were poured in three layers into a Marshall mold equipped with a base and collar after covering the base with filter paper cut to the size of it. Each layer was tamped 15 times around the mold's perimeter and 10 times within the center (ASTM, 2020c). A piece of filter paper similar to the size of mold was placed on the top of the mixture and then subjected to 50 blows on each side by using a mechanical Marshall compactor (Jain and Singh, 2021; Shanbara et al., 2021; Usman et al., 2021). Moreover, Marshall specimens were prepared with varied percentages of RBC to determine the ORBC and OEC. Two steps increment of 0.5% below and above the IEC indicated the bitumen emulsion range. The mixing ranges of RBC and bitumen emulsion for three types of CMA mixtures are presented in Table 6. Three replicates for each sample were prepared, with an average diameter of 101.5 mm and a height of 65.4 mm in accordance with the Marshall specifications (ASTM, 2020c).

2.6. *Design curing after compaction*

In contrast to HMA's curing, which gains its full strength within 24 h after construction, CMA curing takes extra time to attain its full strength. The presence of water in emulsion delays its early strength; when water evaporates slowly, the CMA starts achieving its strength (Jain and Singh, 2021). The present study used the curing period in the AI manual. The CMA samples were left in their molds on their edges after compaction for one day at ambient temperature to obtain similar ventilation on both sides of the sample. The samples were placed in a force draft oven at 40 °C for another 24 h. Finally, the samples were removed from the oven and left at ambient temperature for another 24 h (Thanaya, 2007).

Table 2 – Physical properties of emulsifiers.

Property	Pour point (°C)	Flash point (°C)	Appearance at 20 °C	Viscosity at 20 °C (mPa·s)	Density at 20 °C (g/cc)
Value	<5	>100	Liquid	450	0.93

Table 3 – Physical characteristics of aggregates.

Property	Aggregate		Specification
	Coarse	Fine	
Abrasion value (%)	16.5	16.5	ASTM C131
Impact value (%)	15.6	15.6	BS 812
Specific gravity	2.723	2.678	ASTM C127 & C128
Water absorption (%)	0.5	0.5	–
Aggregate angularity (%)	46	46	ASTM C1252
Sand equivalent (%)	84.2	84.2	ASTM D2419

Table 4 – Physical properties of CMB.

Material	Penetration (25 °C, 0.1 mm)	Softening point (°C)	Viscosity at 135 °C (Pa·s)	PI
CMB	43	57	1.16	0.05

2.7. *Marshall and volumetric properties of CMA*

After designed curing, the cured compacted samples were evaluated for volumetric properties. The volumetric properties of bituminous mixture are important to evaluate because their effect is significant on the permanent deformation and pavement durability. These properties include volume of binder, aggregates specific gravity and density as well as voids in total mixture (VTM), voids filled with bitumen (VFB), voids in mineral aggregate (VMA), and bulk specific gravity (G_{mb}). The theoretical maximum density (TMD) and maximum specific gravity (G_{mm}) are also the critical intrinsic characteristics of bituminous mixture and used to compute the percent of air voids in the compacted mixture. Hence, TMD test was performed on a loose fresh mixture of cold mix in accordance with ASTM D2041. The loose mixture was placed in a vacuum vessel and totally submerged in water. The vessel was subjected to a vacuum up to 30 mmHg and maintained for (15 ± 2) min. G_{mm} was then computed accordingly.

After the volumetric analysis, the compacted samples were evaluated for resistance to the plastic flow with Marshall flow and stability tests in accordance with ASTM D6927. This study adopted the temperature protocols of 60 °C. First, this temperature was selected to simulate the possible adverse conditions on site. Second, it is the upper boundary mixing temperature (0 °C–60 °C) for cold mixture (Usman et al., 2021). Lastly, it enables the comparison of the properties of CMA, such as stability, flow, and volumetric parameters, with that of HMA as recommended by PWD Malaysia (JKR, 2008). A similar temperature (60 °C) for the Marshall stability test of CMA is also suggested by Rezaei et al. (2017).

In this study, CMA cylindrical samples were subjected to a compressive constant loading rate of strain of 50.8 mm per minute in a direction perpendicular to the cylindrical axis until failure occurs. The peak compressive load (in Newton) that leads to the failure of the Marshall samples was measured as the stability value. The corresponding deformation at peak load was measured as the flow value (in units of 0.1 mm). Prior to the stability and flow tests, the Marshall cylindrical samples were tested for bulk specific gravity of the bituminous mixture in accordance with ASTM D2726-21. The results obtained for Marshall and volumetric properties were then evaluated based on the criteria of JKR (2008) specification and AI-MS-14.

The optimum emulsion content (OEC) values were selected on the basis of Marshall parameters such as volumetric properties, stability, and flow values for each mixture. The peak values on each Marshall curve were selected according to the Marshall specification, and their computed average values were considered as the ORBC and OEC. The estimated optimum ORBC values were 7.0%, 6.5%, and 6.5% for CMA-8, CMA-CR, and CMA-6, respectively. The optimum OEC values were 11.3%, 9.8%, and 10.2% for CMA-8, CMA-CR, and CMA-6, respectively.

3. Mechanical performance testing

3.1. *Tensile properties*

3.1.1. *Indirect tensile properties*

An indirect tensile strength (ITS) test was performed to evaluate the quality and initial measurement of rutting and cracking resistance potential of CMA (Ling and Bahia, 2018). A static compressive load was applied in a direction perpendicular to the cylindrical axis of CMA specimens in accordance with ASTM D6931 (ASTM, 2017). Triplicate cylindrical samples were conditioned at 25 °C in a thermostatically controlled water bath for 60 min before ITS

Table 5 – Physical and rheological properties of bitumen emulsions and their residues.

Property	BE-8	BE-CR	BE-6	Specification (MS 2K & SS 1K)	Test method
Saybolt furol viscosity (SFS)					JKR 2008, MS 161, ASTM D977
25 °C	56	74	51	20–100	
50 °C	115	134	112	50–450	
Storage stability test (%)	0.40	0.60	0.50	1.00	
Sieve test (%)	0.10	0.10	0.10	0.10	
Coating	Good	Good	Good	–	
Particle charge test	+	+	+	+	
Evaporation residue (%)	62	66	64	57–65	
Penetration at 25 °C, 0.1 mm	78	51	52	40/60–90/200	
Solubility in trichloroethylene (%)	97.5	97.0	97.5	97.5	

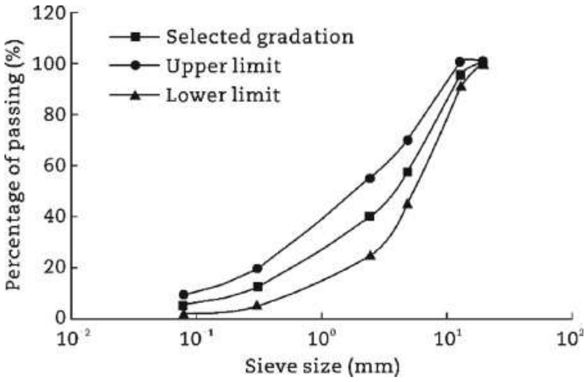

Fig. 3 – Aggregate gradation adopted for preparation of CMA-CR, CMA-8, and CMA-6.

test. The peak load at failure was then recorded nearest to 1 N, and ITS was computed to the nearest 10 kPa. Similarly, wet ITS was also determined at 25 °C after moisture conditioning another set of samples in a water bath at 60 °C for 24 h.

3.1.2. *Indirect tensile stiffness modulus (resilient modulus)*

An indirect tensile resilience modulus test was applied to measure the stiffness modulus and determine the effect of temperature and loading on the durability of cold bituminous mixture. It is a non-destructive test that reflects the mixture response to fatigue. Resilient modulus (M_R) is used as a significant parameter in the mechanistic design and analysis of pavement layers. M_R is a ration of deviator stress over a recoverable horizontal stain (Ameri et al., 2022). Hence, it decides the thickness of pavement layer. M_R is a ration of deviator stress over a recoverable horizontal stain (Ameri et al., 2022).

Three specimens were prepared at OEC for each binder type in accordance with ASTM D6926-20 (ASTM, 2020c). Prior to testing, the specimens were conditioned in UTM-5 universal testing machine chamber for 4 h at 25 °C and 40 °C. The cylindrical specimens were subjected to haversine waveform load of the maximum pulse load of 1 kN on a vertical diametrical plane with 0.1 s load duration and 0.9 s rest period. Five pulses of maximum compressive load were applied for each specimen at a position and repeated it at 90° by rotating the sample in accordance with ASTM D7369-20 (ASTM, 2020a). Total recoverable horizontal and vertical deformation was recorded based on the estimated value of Poisson's ratio of 0.35.

Table 6 – Bitumen emulsion and RBC range.

Mixture type	Mixing range	
	RBC (%)	Bitumen emulsion (%)
CMA-8	–	8.87–12.10
CMA-CR	5.5–7.5	8.3–11.4
CMA-6	–	8.6–11.7

3.2. *Resistance to rutting*

3.2.1. *Dynamic creep test*

Resistance to rutting of the bituminous mixture can be assessed through dynamic creep test. A cyclic compressive load is applied to simulate the traffic and assess the rutting after each repeated load (Nassar et al., 2018). In the present study, the Marshall specimens with three replicates were conditioned at 40 °C for at least 4 h prior to testing. The samples were then subjected to repeated axial stress of 300 kPa with a confining stress of 100 kPa. A preconditioning stress load of 150 kPa with 30 cycles was applied to equalize the stress concentration on the surface of the loading plates and the samples. The test either stops after the completion of 3600 cycles or achieves an accumulated axial strain of 5%. The specimens' conditioning, loading limitations, and creep modulus computation were in accordance with the recommendation of PWD Malaysia and British standards (BSI, 2013; JKR, 2008).

3.2.2. *Wheel tracking test*

A double-wheel tracking (DWT) test was used to determine resistance to the permanent deformation of CMA under repeated application of loaded wheels in accordance with EN 12697-25 standard procedure (BSI, 2013). This test quantifies the high temperature performance of bituminous mixture in laboratory (Babagoli et al., 2016; Shanbara et al., 2018a). A cylindrical sample (150 mm × 75 mm) was compacted with gyratory compactor with 7% ± 0.5% air voids (Fig. 4(a)). The samples were then conditioned at 50 °C for 4 h in a temperature-controlled chamber of DWT equipment (Fig. 4(b)). Finally, the samples were subjected to dynamic loaded wheels at a speed of 26.5 cycles per minute. The test included the failure criteria of reaching a maximum rut depth of 20 mm or total number of 10,000 load cycles.

3.3. *Moisture susceptibility*

3.3.1. *Tensile strength ratio (TSR) test*

The moisture sensitivity of bituminous mixtures can be evaluated through TSR test. Six cylindrical samples were prepared and sorted into wet and dry subsets in accordance with ASTM D4867 (ASTM, 2014). Generally, the TSR samples for HMA are compacted within the range of 6%–8% air voids but it cannot be achieved for the CMA. Therefore, the air voids at OEC were considered for the preparation of CMA mixtures. Moreover, the dry subset was tested at 25 °C. Similarly, the wet subset was initially saturated to achieve 55%–80% degree of saturation by applying vacuum pressure of 70 kPa for 5 min. The wet sample was tested at 25 °C after moisture conditioning in a water bath at 60 °C for 24 h. TSR was then computed from both sets of samples.

3.3.2. *Modified stripping test*

Boiling test for bituminous aggregate is conducted to quantify the adhesion of bituminous mixture in the presence of water (Li et al., 2019). Furthermore, it provides an indicator to measure the moisture susceptibility, stripping resistance, and durability of bituminous mixtures (Abdulrahman et al., 2021; Attaran Dovom et al., 2019). A 250 g of loose CMA

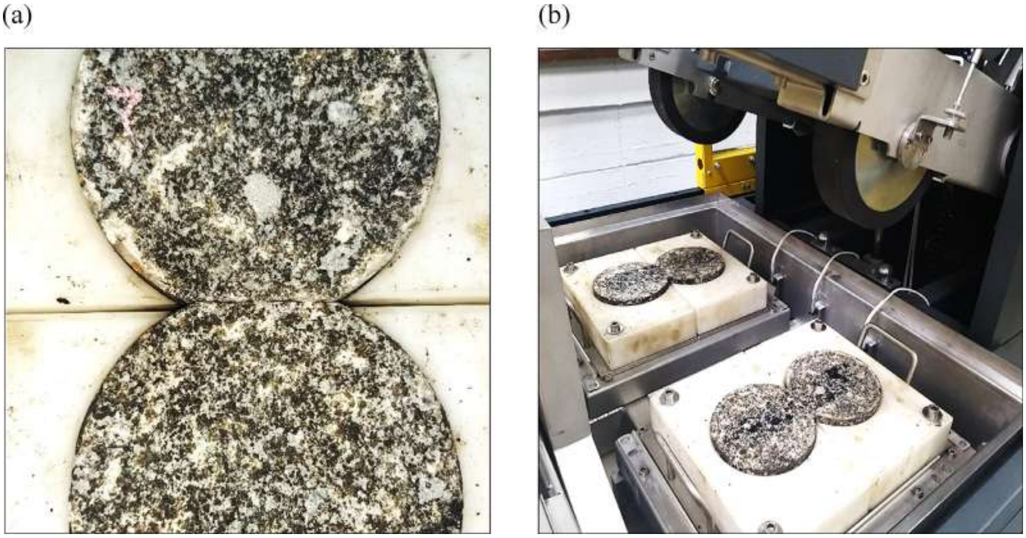

Fig. 4 – DWT test. (a) Prepared and fixed samples in the mold. (b) Conditioning of samples in the DWT chamber.

mixture was subjected to boiling for 10 min in a beaker containing distilled water following the ASTM D3625 standard (ASTM, 2020b). The water surface was skimmed off from any free available bitumen to avoid recoating of aggregates after the removal of beaker from the heat source as shown in Fig. 5. The sample was allowed to cool to room temperature, collected from the beaker, and then dried. This test was performed for two other representative samples to produce three replicates. The samples were then photographed from a right angle at sufficient lighting. The photographs were converted into blue colored format by using an image processing tool in MATHLAB (adaptive thresholding) (Attaran Dovom et al., 2019; Ling et al., 2016). Finally, the coating before and after boiling was determined for evaluation.

Fig. 5 – A surface to be skimmed during boiling test to avoid recoating.

3.4. *Durability test*

3.4.1. *Cantabro loss test*

The durability of bituminous mixture can be evaluated through Cantabro loss test. This test is used to evaluate the adhesion and cohesion characteristics of bituminous mixtures. The method suggested by the Texas Department of Transportation (2014) was adopted. A set of three cylindrical samples were prepared and subjected to 300 revolutions in an LA machine at 30–33 RPM without bearings. The percentage weight loss of the sample was determined before and after the test. The least loss of the percentage mass of the bituminous mixture after the Cantabro test led to sufficient durability.

4. Results and discussion

4.1. *Analysis of volumetric and Marshall properties*

Volumetric properties including VTM, VFB, VMA, and densities of CMA-8, CMA-CR, and CMA-6 are given in Table 7. The percentage of air voids filled with bitumen in the CMA-CR was higher than those of the two other conventional mixtures. The percentage of VFB significantly increased from 55.4% to 56.4% because of the rubberized binder. This finding may be attributed to the higher bitumen film thickness of the CLR-modified binder caused by the higher viscosity of CMB (Azahar et al., 2019). The CMBE used in the preparation CMA-CR also contained additional amount of emulsifier in the end bitumen residue after water evaporation (Ghafar et al., 2022a), as represented by the higher workability of the mixture during mixing and compaction (Abdulrahman et al., 2021). This phenomenon also resulted in higher VFB and density than the other mixtures. The VFB value for CMA-6 was 50.7% which was lower than those of CMA-8 and CMA-CR. The harder grade bitumen used in the emulsion led to compaction resistance. The VFB results were supported by VTM values, indicating that the air voids in the CMA-CR mixture decreased from 10.5% to 9.7% because of the rubberized binder. CMA-6 resulted in a higher percentage of air voids than CMA-8 and CMA-CR. The results of VMA and densities for the three mixtures were comparable. The VMA values were 25.8%, 24.0%, and 26.2% for CMA-8, CMA-CR, and CMA-6, respectively. CMA-CR exhibited slightly higher density than the other mixtures. The difference between the density values of CMA-8 and CMA-6 was not obvious.

Table 7 summarizes the stability, flow, and stiffness results of CMA-8, CMA-CR, and CMA-6. CMA-CR resisted higher load in terms of stability compared with CMA-8 and CMA-6. The stability values of CMA-CR were 5.8% and 4.0% higher than those of CMA-8 and CMA-6, respectively. The existence of CLR rubber in the bitumen residues sustained higher load (Abdulrahman et al., 2021). Furthermore, the polymeric properties of CLR rubber created a cross-linked structure in the modified bitumen emulsion, thereby preventing the deformation under the load (Ansari et al., 2022; Ghafar et al., 2022b). The CMA-CR exhibited higher flow value than the two other bituminous mixtures. The flow values were 2.73, 3.22, and 2.79 mm for CMA-8, CMA-CR, and CMA-6, respectively. In addition, the CMA-CR followed the stress-strain relationship. Therefore, higher strain in terms of flow sustained higher stress in terms of stability load because the CLR rubber possessed higher elastomeric properties (Azahar et al., 2021). This phenomenon further contributed to the stress-strain phenomenon and enhanced the stiffness. Finally, CLR enhances the bonding between bitumen and the aggregates of CMA-CR through sufficient adhesion potential (Azahar et al., 2019), leading to resistance to CMA damage in terms of cracking.

4.2. *Indirect tensile strength*

The ITS strength indicates the potential of adhesion and cohesion of bituminous mixtures (Attaran Dovom et al., 2019). In general, the dry ITS strength of bituminous mixtures is higher than that of wet ITS because moisture trapped in the mixture tends to separate aggregates and bitumen, thereby reducing the adhesion strength (Mirabdolazimi et al., 2021). The results of dry ITS and wet ITS of CMA containing CLR and other control mixtures are presented in Fig. 6. The CMA-CR had higher tensile strength than CMA-8 and had almost similar value to CMA-6 in terms of dry and wet ITS. Moreover, CLR rubber significantly enhanced the ITS of CMA-CR by 26%. Thus, the CLR modification obtained the mixture's performance comparable to CMA-6 which was prepared from bitumen emulsions of higher penetration grade. CLR has the potential to create a cross-linked network, which increases the cohesion and bonding strength of the modified mixture by well filling the pores on the aggregate surface. However, the wet ITS of the CMA-CR was higher than that of its dry ITS (Fig. 6). This finding may be attributed to the OPC hydration process and temperature. The additional hydration process of OPC is activated during conditioning, leading to enhanced early strength. The results are also consistent with previous literature (Al-Hdabi et al., 2014; Al-Nageim et al., 2012; Dulaimi et al., 2016, 2017; Nassar et al., 2018) but was not observed in the CMA-8 mixture.

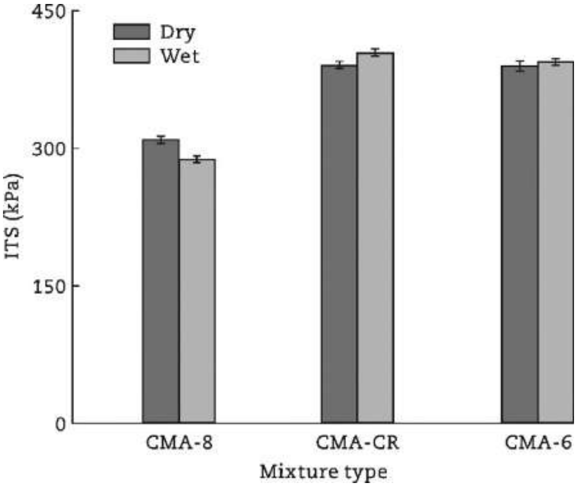

Fig. 6 – ITS (dry and wet) results representing comparable strength between CMA-8, CMA-CR, and CMA-6 mixtures.

Table 7 – Volumetric and Marshall properties of CMA-8, CMA-CR and CMA-6.

Property	CMA-8	CMA-CR	CMA-6
Volumetric property			
VTM (%)	10.5	9.7	12.5
VFB (%)	55.4	56.4	50.7
VMA (%)	25.8	24.0	26.2
Density (lb/ft^3)	131.1	133.8	131.2
Marshall property			
Stability (kN)	6.9	7.3	7.0
Flow (mm)	2.73	3.22	2.79
Stiffness (N/mm)	2536.3	2626.1	2644.4

4.3. *Indirect tensile stiffness modulus (resilient modulus)*

Resilient modulus is the elastic response of a bituminous mixture to cyclic loading of traffic under different climatic conditions (Ali, 2022; Gupta and Kumar, 2022); it is computed based on viscoelastic characteristics, such as applied dynamic stresses and corresponding recoverable strain of the mixture (Zahid et al., 2022). The M_R results for CMA-8, CMA-CR, and CMA-6 at 25 °C and 40 °C are presented in Fig. 7. CMA-CR had higher M_R value than CMA-8 and CMA-6. The CLR rubber substantially increased the M_R value of CMA-CR by 24% and 19% at 25 °C and 40 °C, respectively. The M_R results of CMA-CR also presided over the values of CMA-6 by 14% and 9% at 25 °C and 40 °C, respectively. The strain in the bituminous mixture increases proportionally with increasing temperature (Sarella et al., 2022). However, the effect of temperature on the M_R of CMA-8, CMA-CR, and CMA-6 was measured to be 10%, 11%, and 11%, respectively. The effect of temperature difference among the different

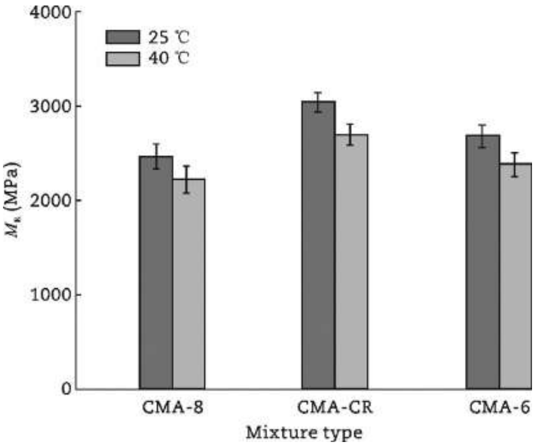

Fig. 7 – M_R results showing comparable strength between CMA-8, CMA-CR, and CMA-6 mixtures at 25 °C and 40 °C.

mixture types was insignificant. Hence, CLR rubber contributed to the resilience and elastic properties of CMA-CR, thereby promoting the cohesion between aggregates and binder and improving the stiffness of the bituminous mixture (Abdulrahman et al., 2021; Azahar et al., 2019). These findings are also in line with the physical properties of CLR-modified bitumen and bitumen emulsion (Ansari et al., 2022; Azahar et al., 2021; Ghafar et al., 2022a).

4.4. *Dynamic creep test*

Resistance to permanent deformation of bituminous mixtures could be attributed to the thermal viscoelastic properties of binder used in the mixture design. The properties of binders vary in accordance with temperature variation (Gupta and Kumar, 2022). Gradation, compaction, and aggregate coating also affect the rutting potential of bituminous mixtures. Creep can occur in three different stages according to the slope of the creep curve. The strain rate is initially very high and starts decreasing with time at the initial stage. Creep in terms of strain remains constant in the second stage, and the growth of strain starts abruptly in the final stage (Jiang et al., 2018; Shanbara et al., 2018b). The results of the dynamic creep test in terms of permanent strain, creep stiffness modulus (CSM), and creep strain slop (CSS) are summarized in Figs. 8–10.

Fig. 8 presents the permanent strain versus 3600 loading pulse applications for CMA-8, CMA-CR, and CMA-6. The CMA-CR had the lowest strain and enhanced resistance to deformation compared with CMA-8 and CMA-6. The accumulative strain values were 13,983, 10,566, and 12,875 με for CMA-8, CMA-CR, and CMA-6, respectively (Fig. 9). This finding may be attributed to binder modification with CLR, leading to enhanced elastic behavior of the CMA-CR mixture. It also improved the resistance to permanent deformation and decreased the strain value (Abdulrahman et al., 2021; Azahar et al., 2019). CMA-6 had higher resistance to deformation than CMA-8 but lower than CMA-CR possibly due to the higher percentage of air voids in the mixture.

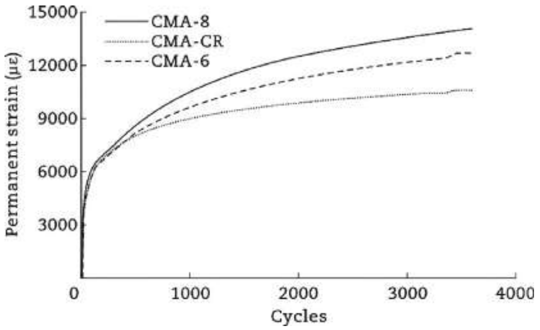

Fig. 8 – Dynamic creep test results showing the plot of strain versus repetition cycle for CMA-8, CMA-CR, and CMA-6.

The results of CSM and CSS are depicted in Figs. 9 and 10, respectively. CMA-CR possessed the highest CSM value of 43.5 MPa. The CSM of CMA-CR increased by approximately 100% with the addition of CLR. The CSM of CMA-6 was 22.5 MPa, which was slightly higher than that of CMA-8. A higher CSM indicates that the mixture has higher stiffness and potential of resistance to deformation (Ameri et al., 2022). The results of CSM were further supported by CSS values as shown in Fig. 10. The CSS of each mixture were computed from the slope of the creep curve in the secondary stage, wherein the rate of deformation under repeated load remains constant (Radeef et al., 2022). Moreover, the CMA-CR had the lowest CSS value of 0.12 compared with the other mixtures (Fig. 10). This finding indicated that deformation occurred in the initial stage of creep curve. A lower value of CSS represents more resistance to permanent deformation and higher stiffness (Ali, 2022). Hence, the CLR rubber improved the CSS value of the CMA-CR mixture by 50%. These results were correlated with the M_R and ITS data. Similarly, the results of the dynamic creep test were consistent with previous works on CLR-modified asphalt (Abdulrahman et al., 2021; Azahar et al., 2019).

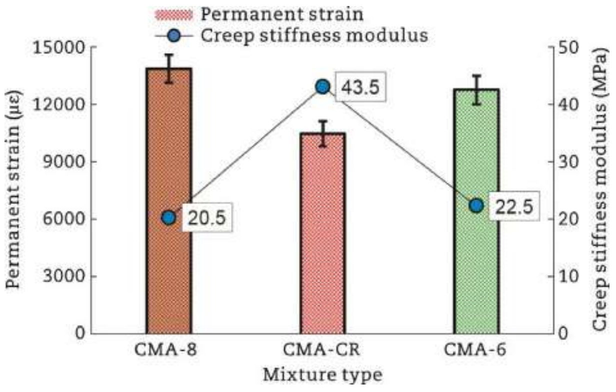

Fig. 9 – Dynamic creep test results showing permanent strain and creep stiffness modulus of CMA-8, CMA-CR, and CMA-6 mixtures.

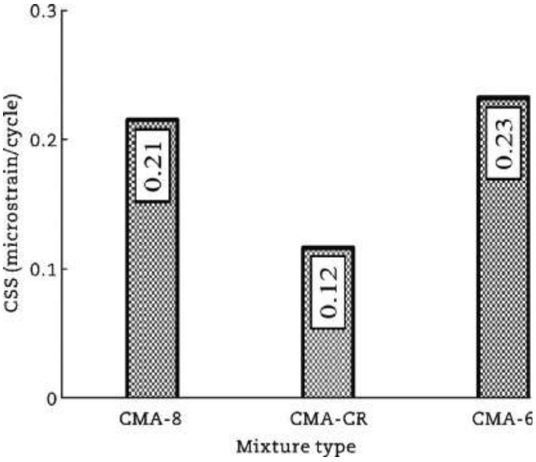

Fig. 10 – Results of creep strain slope.

4.5. *Wheel tracking test*

Permanent deformation refers to rutting produced from repeated loading of wheels on the bituminous surface of pavements at an elevated temperature (Amoori Kadhim et al., 2022). Therefore, it is considered one of the major distresses of asphalt pavement (Abdel-Wahed et al., 2022). Higher rut depth means higher permanent deformation in asphaltic pavement, leading to shorter service life (Dulaimi et al., 2016; Shanbara et al., 2018a). The results of the wheel tracking test are presented in Figs. 11 and 12. The rate of rutting was higher in the initial stage of load passing, between 0 and 2000 passes of loads. The high rate of permanent deformation decreased at the end of the initial stage (Fig. 11). The abrupt increase in the initial stage can be associated with mixture densification under dynamic loading, leading to a higher rate of rutting. The rate of rutting then decreased and remained constant in the secondary stage because of permanent shear deformation due to stresses in the mixture (Babagoli et al., 2016; Radeef et al., 2022).

Fig. 12 shows that the resistance to permanent deformation in CMA-CR increased by 70% when modified with CLR. The potential of resistance to rutting in CMA-CR was 30% higher than that in CMA-6. The final rut depths were 2.56, 0.76, and 1.13 mm for CMA-8, CMA-CR, and CMA-6, respectively. Meanwhile, the CMA's rutting performance could not be compared with HMA mixture due to their weak mechanical strength (Deb and Lakshman Singh, 2022). Radeef et al. (2022) and Al-Saffar et al. (2021) found the rutting values to be 3.3 and 1.97 mm for HMA mixtures, respectively. By comparing their results with that of CMA-CR, the rutting value was even greater than HMA mixtures. Because CLR enhanced the bonding strength and interlocking structure of CMA-CR mixture. Furthermore, the addition of CLR to the modified bitumen created a cross-linked structure by forming a more stable structure, thereby enhancing the binding and elastic properties of CMB (Cai et al., 2020; Ghafar et al., 2022a). In addition, CLR modification created a thick film coating on the surface of aggregates. The evaporation residues of CMB absorbed excessive stresses and prevented the slippage of aggregates in the mixture (Radeef et al., 2022; Sun et al., 2022). Thus, it enhanced the resistance to the permanent deformation of the CMA-CR (Abdulrahman et al., 2021). Hence, the CMA-CR may be effective in rutting resistance. These results had good correlation with the ITS, M_R, and creep data.

4.6. *TSR results*

The potential of resistance to moisture damage is an important factor in the long-term performance of bituminous mixtures (Shanbara et al., 2018a). The TSR results are presented in Fig. 13. The TSR values were 93%, 104%, and 101% for CMA-8, CMA-CR, and CMA-6, respectively. This finding indicated that the resistance of CMA-CR to moisture damage significantly improved by 11.8% with CLR modification. However, the TSR values of CMA-CR were almost similar to those of CMA-6, confirming the upgrading of the penetration grade with CLR modification (Ghafar et al., 2022b, 2022c). The minimum TSR value for the bituminous mixture is 80%

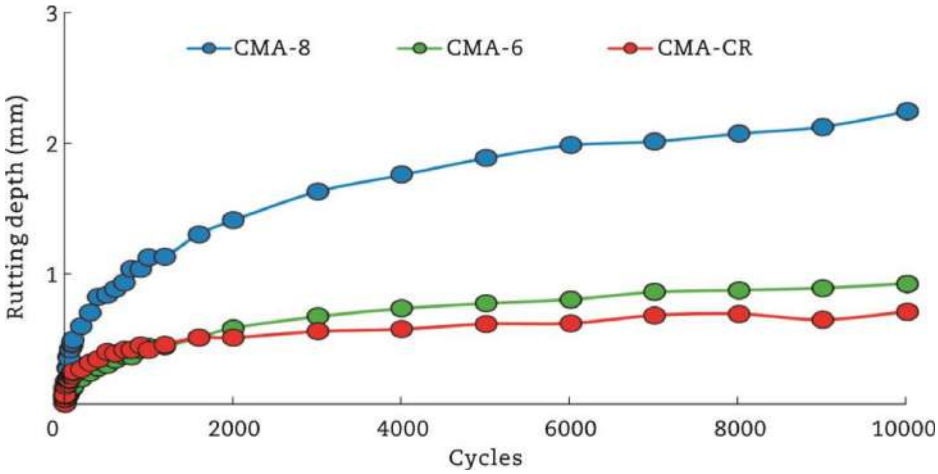

Fig. 11 – Wheel tracking test results showing the plot of rutting versus loading cycle for CMA-8, CMA-CR, and CMA-6 mixtures.

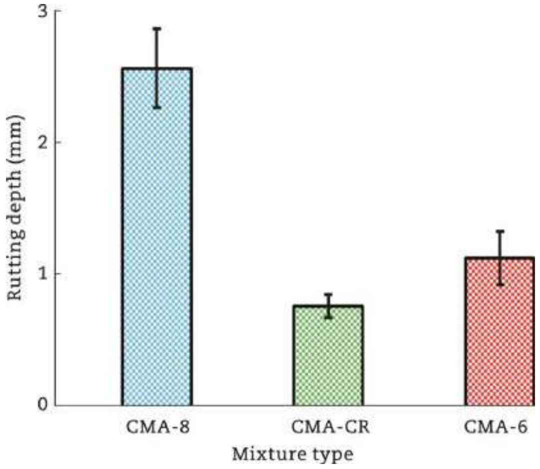

Fig. 12 – Wheel tracking test results showing the rutting resistance for CMA-8, CMA-CR, and CMA-6 mixtures.

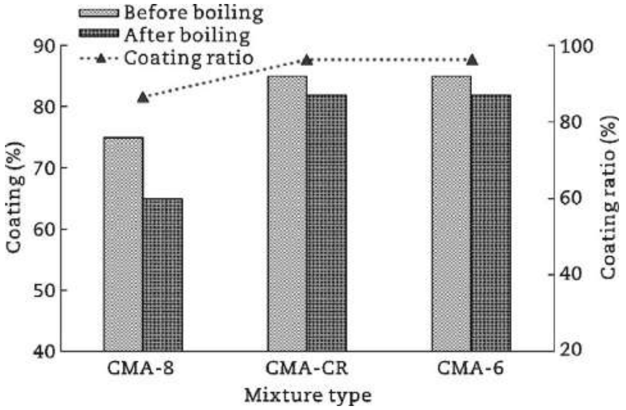

Fig. 14 – Coating before and after boiling and coating ratios for CMA-8, CMA-CR and CMA-6.

as recommended by AASHTO T283 (Usman et al., 2021) because it also passes the minimum criterion for all types of CMA mixtures. The TSR values of CMA-CR and CMA-6 were greater than 100% due to the hydration process of OPC and temperature, as discussed in section 4.2 (Nassar et al., 2018). Finally, the cohesion and adhesion potentials of CMA-CR were enhanced, thereby increasing the resistance to moisture damage (Ling et al., 2016).

4.7. *Stripping measurement*

Fig. 14 shows that the coating of the CMA-CR mixture before boiling was higher than that of CMA-8 and similar to that of CMA-6. However, the initial bitumen coating in conventional mixtures, such as HMA, is achieved by 100% during mixing, and the threshold is set to 95% (Abdulrahman et al., 2021). The criteria in the case of CMA is 50% only, and complete coating cannot be achieved (Jain and Singh, 2021). Based on the analysis of the images, CLR increased the coating of CMA-CR significantly by 10% (Fig. 15(b)). The boiling effect was adverse on CMA-8 without CLR (Fig. 15(a)), resulting in 7% higher adhesion loss compared with the 3% only for CMA-CR and CMA-6. No significant change was observed between CMA-CR and CMA-6 before and after boiling (Fig. 15(b) and (c)) because of their comparable physicochemical characteristics. The coating ratios were 87%, 96%, and 96% for CMA-8, CMA-CR, and CMA-6, respectively (Fig. 14). The polymeric property of CLR makes the binder of CMA-CR capable of resisting adhesion loss and prevented stripping (Attaran Dovom et al., 2019; Azahar et al., 2021; Li et al., 2019).

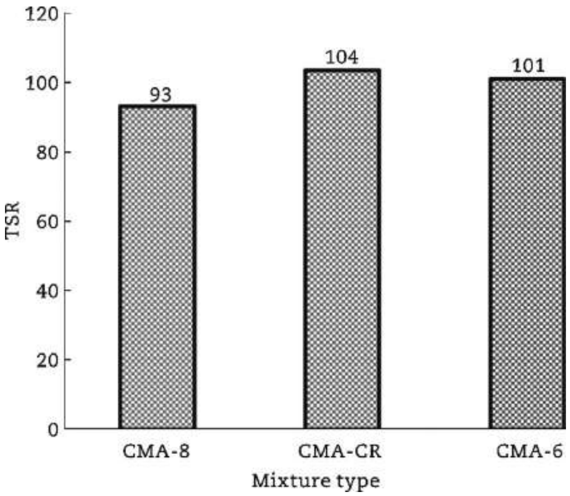

Fig. 13 – TSR results of CMA-8, CMA-CR, and CMA-6 mixtures.

4.8. *Cantabro loss results*

The results of Cantabro test in terms of percentage mass loss are presented in Fig. 16. The mass loss rates were 18.5%, 14.6%, and 15.7% for CMA-8, CMA-CR, and CMA-6, respectively. The maximum accepted limit of percentage mass loss for bituminous mixtures is 20% (Ferrotti et al., 2014). CMA-8 had the highest mass loss compared with CMA-CR and CMA-6. The modified bitumen emulsion with CLR significantly decreased the percentage mass loss of the CMA-CR mixture by 21%. CMA-6 ranked second in terms of performance and had 15% higher resistance to mass loss than CMA-8. However, CMA-6 did not resist mass loss compared with the CMA-CR.

Previous studies indicated that mass loss in the Cantabro test depends on several parameters of bituminous mixture and its binder. These parameters include penetration grade, viscosity, aggregate gradation, and air voids (Doyle and Howard, 2016; Tian et al., 2011). Furthermore, emulsions prepared with the polymer-modified bitumen had enhanced bonding and cohesive strength. The polymer in the modified bitumen created a cross-linked structure, which promoted the adhesion performance of the bituminous mixture (Usman et al., 2021). Thus, CLR modification improved the physical properties of the modified bitumen emulsion and resulted in lower percentage mass loss. The higher

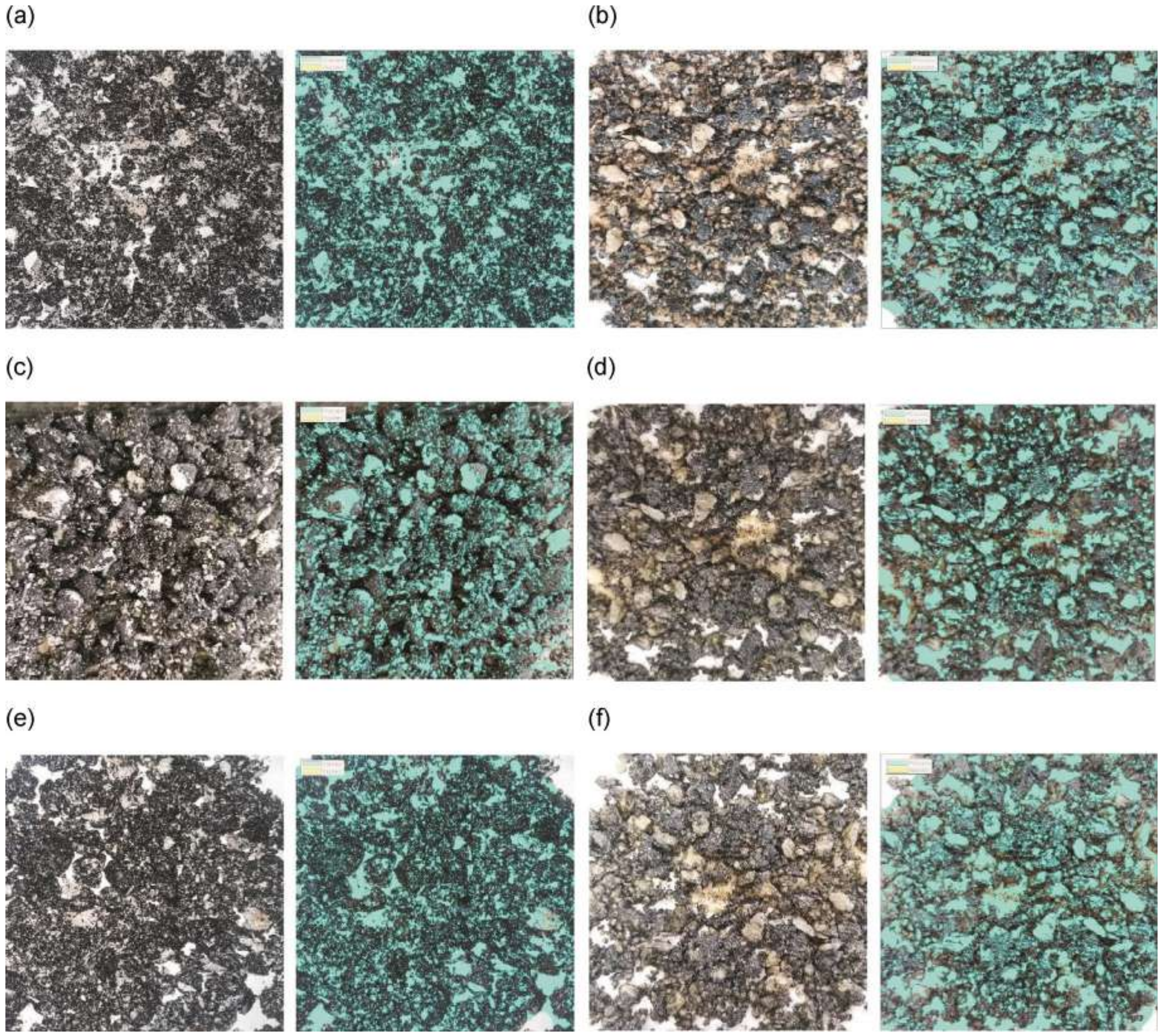

Fig. 15 – Digital imaging analysis before and after boiling. (a) CMA-8 before boiling. (b) CMA-8 after boiling. (c) CMA-CR before boiling. (d) CMA-CR after boiling. (e) CMA-6 before boiling. (f) CMA-6 after boiling.

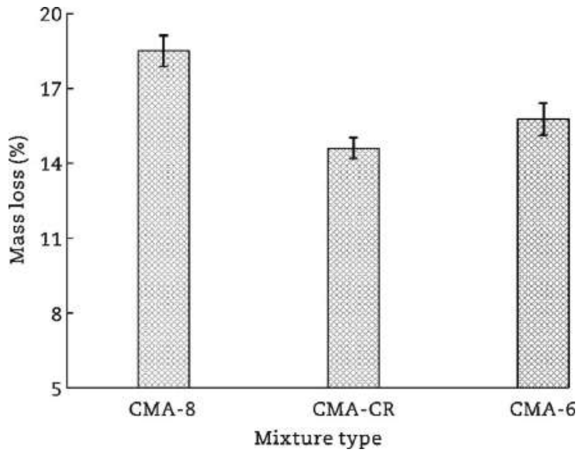

Fig. 16 – Comparison of Cantabro loss results of CMA-8, CMA-CR, and CMA-6.

percentage mass loss of the CMA-6 may be attributed to the higher number of air voids in the total mixture. These findings were consistent with the stripping results.

5. Conclusions

This study evaluated the mechanical performance of CLR-modified bitumen emulsion in CMA mixture. The tensile properties, rutting potential, moisture damage, and durability of CLR in CMA mixture were investigated. The CLR has the potential to be employed as an efficient bio-modifier of bitumen emulsions. Based on the evaluation of tensile properties, the CLR improved the cracking resistance of the CMA mixture. Similarly, the CMA-CR prevented the rutting, representing 70% improvement compared with unmodified CMA mixture. The moisture susceptibility results indicated that the rubberized mixture had excellent stripping resistance by retaining more than 95% coating. The TSR value was 104% and increased significantly by 12% with CLR modification. The mixture durability was further improved by 21% by preventing mass loss compared with conventional CMA. The mechanical performance of the CMA-CR was comparable and even higher than that of the CMA mixture prepared from emulsified bitumen of 60/70 PEN grade. The life of CMA pavement can be extended by adding CLR as a modifier in emulsified bitumen. Future research should be conducted to investigate the field performance of CMA-CR mixture and to analyze the life cycle of the CMA-CR mixture.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

Acknowledgments

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